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Variability of small scale model reinforced concrete and implications for geotechnical centrifuge testing

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ABSTRACT: There are soil-structure interaction problems for which it is important to model both the relative soil-structure stiffness and strength. Examples from the earthquake engineering field include the design of resilient rocking-isolated foundations and the seismic stabilisation of slopes using piling. In both cases the aim is to ensure a preferred failure mode happens first in the soil instead of the structure i.e. controlled bearing failure of the foundation or soil yielding around piles. A recently developed model reinforced concrete for centrifuge testing can simulate stiffness and strength simultaneously, but suffers from variability in the material properties, as does the full-scale material. This paper presents a series of element tests on the variability of model reinforced concrete elements representative of large square monolithic bridge piers and slender square piles. Coefficients of variation for various material and element properties have been determined and shown to be similar to typical values for full-scale reinforced concrete elements obtained from the literature. It is also demonstrated that curing time beyond 28 days does not substantially affect strength and variability and that models of different absolute volume can be produced without inducing detrimental size effects. The results are used to discuss the selection of mean design strengths for model structural elements in centrifuge experiments using a quantitative statistical approach where there are competing structural and soil failure modes.

1 INTRODUCTION

While for many soil-structure interaction problems it is possible to identify a single non-dimensional parameter to ensure sufficient similitude when testing physical models in a geotechnical centrifuge, there also exist a number of important problems for which this is not the case. These are typically cases in which one of the possible failure modes is associated with the structural elements of the soil-structure system in question. In such cases it is important to achieve similitude of both the relative soil-structure stiffness and relative soil-structure strength. The former is important to ensure that the kinematic demands on the soil and structural elements are representative as the system approaches failure; the latter, to ensure that the appropriate ('weakest') failure mode is reached first, whether that is associated with the soil failing around the structure, or the structure failing before the soil.

Examples of such problems often occur in earthquake engineering, where high kinematic demands and failure may be unavoidable within design. These include assessing the performance of rocking-isolated structures (e.g. bridge piers on shallow foundations, Loli et al., 2014), pile reinforcement of slopes against seismic effects (e.g. Al-Defae and Knappett, 2014) or damage to foundation pile groups due to liquefaction-induced lateral spreading (e.g. Stergiopoulou et al., 2016). In each of these aforementioned examples, the potentially damageable elements (piers or piles) were modelled using a novel micro reinforced concrete ('model RC') developed at the University of Dundee (Knappett et al., 2011) which can simultaneously achieve similitude of stiffness, strength and ductility at scaling factors suitable for centrifuge use.

This modelling approach involves combining a quasi-brittle cementitious material (plaster-based mortar) with discrete steel wires, as a geometrically scaled model of reinforced concrete. One of the implications of this, however, is that model RC elements will exhibit greater variability in key material properties (e.g. bending stiffness, EI and moment capacity, M_{ult}) than equivalent 'elastic' models (made typically out of aluminium alloys, steel or plastics). If this variability is similar to that of field reinforced concrete, this would potentially represent another way in which the model RC is a closer analogue of field concrete.

This paper will address this issue of variability by presenting test data of both the variability in fundamental mechanical properties of the individual material components (e.g. compressive strength and tensile strength of the model concrete; yield strength of the model reinforcement) and of full reinforced concrete structural elements. This will be compared with extensive data from the literature for field reinforced concrete. The elements tested will be based on those used in recent geotechnical centrifuge testing programmes, and the results will be used to discuss the implications of variability on model design, using the example of a reinforced concrete bridge pier on a foundation designed to provide rocking-isolation under seismic actions.

2 TEST PROGRAMME

A series of both reinforced and unreinforced elements were cast using the materials introduced in Knappett et al. (2011). A total of 23 cube compression tests are reported herein, alongside 10 model reinforcement tension tests, 21 four-point bending tests on unreinforced model concrete beams (prisms) of different model sizes and 20 four-point bending tests on reinforced model RC elements of different size and reinforcement ratio, consisting of both singly-reinforced slender beams and stockier uniformly reinforced sections.

2.1 *Model materials and element tests*

Table 1 summarises the key compressive properties and variability of the model concrete materials, while Table 2 summarises the key tensile properties and variability. Compressive strengths ($f_{cu,100}$) were determined from crushing tests on 100 × 100× 100 mm cubes; mean strength and coefficient of variation (COV) are shown in Table 1, across the n samples tested. All cubes were cured for t_{cure} = 28 days before testing.

Table 1 Model concrete cube compression testing results

Mix*	t_{cure} (days)	n	$\bar{f}_{cu,100}$ (MPa)	COV
1	28	11	26.3	0.128
2	28	6	35.6	0.150
3	28	6	50.9	0.086

* as defined in Knappett et al. (2011)

Tensile strength was quantified by the modulus of rupture (f_r), determined from the maximum force (V_{ult}) applied at brittle failure of an unreinforced rectangular prism, loaded as a beam in a four-point bending test. The modulus of rupture represents the breaking strength at the edge of the beam on the tension side of the beam on the tension side, and can be considered to be the most representative tensile strength relating to the behaviour of reinforced elements in transverse bending.

Ten of the prisms were 10 mm × 10 mm in cross-section and 200 mm long and cured in air for 28 days before testing, while the remaining eleven were 30 mm × 30 mm in section and 200 mm long and cured for variable lengths of time before testing, between 14 – 122 days. By varying the curing length it will be possible to assess whether delays in a programme of centrifuge testing since curing would significantly affect the material properties of the model concrete.

Modulus of rupture is typically the parameter of a quasi-brittle material which is most sensitive to unwanted size effects, due to the likelihood of a larger crack existing within a specimen of larger volume. The prism dimensions considered here, while selected to match the later reinforced element tests (due to appropriate formwork being available for casting), demonstrate nearly one order of magnitude (a factor of nine times) difference in actual volume at model scale between the two sets of tests. This variation will therefore allow a fuller investigation of size effects than conducted in previous work (e.g. Knappett et al. 2011).

In the four-point bending tests, the distance (L) between supports was set at 180 mm (with the beam overhanging the supports at each end by 10 mm) and symmetrical vertical shearing loads were applied at 60 and 120 mm from one of the supports (i.e. a shear span of a = 60 mm). The modulus of rupture was then found using:

{ EMBED Equation.3 }
(1)

where b = beam breadth and d = beam depth.

All 21 prisms were cast using Mix 1 model concrete (see Table 1), and the basic test results are given in Table 2.

Table 2 Model concrete modulus of rupture testing

Size (mm)	t_{cure} (days)	n	$\bar{f}_r$ (MPa)	COV
10 × 10	28	10	2.02	0.149
30 × 30	variable	11	2.62	0.121

2.2 *Model RC elements*

Reinforced (model RC) elements were fabricated to different designs, representing (i) the 1:50 scale singly-reinforced piles used for slope stabilisation in the centrifuge tests reported by Al-Defae and Knappett (2014) and (ii) the 1:50 scale Eurocode 8 compliant square concrete bridge pier used in the centrifuge

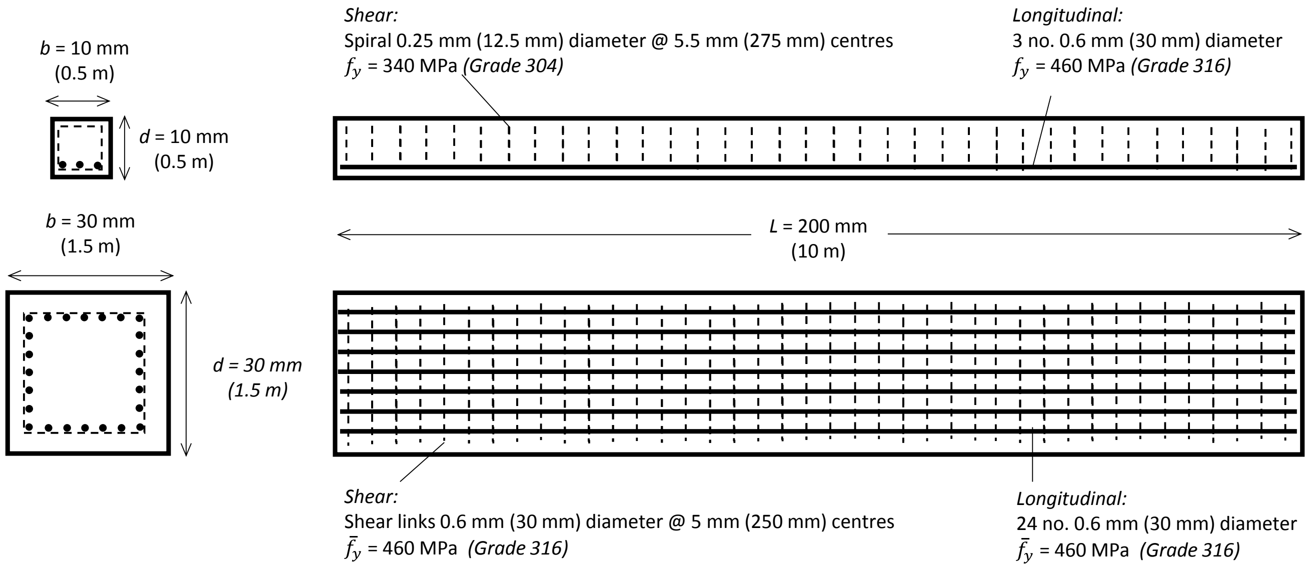

Figure 1 Reinforcement layout of model RC beams. Dimensions are model scale (prototype scale for 1:50 in brackets).

tests reported by Loli et al. (2014). These share the same exterior dimensions as the prisms cast for modulus of rupture testing described above, but containing model longitudinal and shear reinforcement modelled using drawn stainless steel wire (Grade 316 or 304) which was roughened for bond by gluing on a coating of fine sand (see Knappett et al., 2011 for further details). The reinforcement layouts are shown in Figure 1 and some key mechanical properties are summarised in Table 3.

Table 3 Model RC element testing

Type	Size (mm)	t_{cure} (days)	n	M_{pr} (kNm)
Pile	10 × 10	28	10	230
Pier	30 × 30	28	6	4500
Pier	30 × 30	variable	4	4500

M_{pr} in Table 3 represents the prototype Moment capacity that the sections simulate. The beams were tested in four-point bending using the same loading arrangement as for the modulus of rupture tests described above. It should be noted that the larger pier section was tested under zero axial load (though it would be used as a column in a centrifuge model). The model pier tests included some that were cured for longer periods than 28 days, to examine how any change in properties from curing (e.g. in f_r) may manifest in the global response of the reinforced element.

Ten sample lengths of Grade 316 stainless steel wire were tensile tested within an Instron 1196 load frame to evaluate the variability in the yield strength of the steel (f_y), which was evaluated at 0.2% strain for consistency with conventional definitions of this parameter for tests on steel reinforcing bar.

3 VARIABILITY OF MODEL RC ELEMENTS

3.1 *Material components*

Figure 2 shows a comparison of the compressive strength of the model concrete against data for conventional concrete collected from the literature (as detailed in the figure). It is clear that for the conventional data there is a significant difference in variability (as expressed by *COV*) between concrete mixed and placed in-situ, and that produced under laboratory conditions. The comments on quality control shown in the figure are as proposed by Walker (1955). It can be seen that the model concrete, prepared using the procedures outlined in Knappett et al. (2011), appears to have variability of compressive

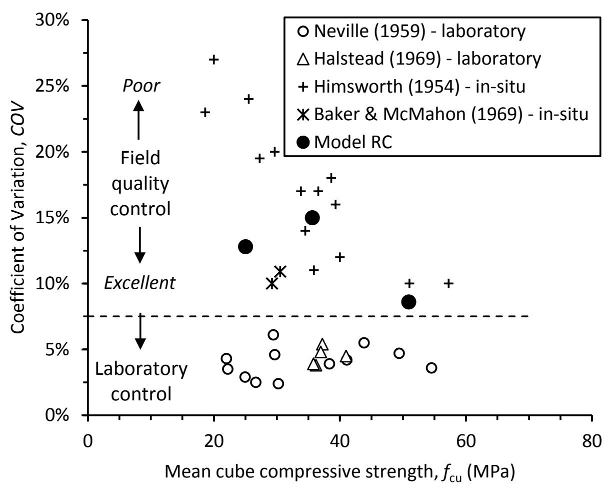

Figure 2 Variability of model concrete compressive strength compared to typical values for conventional concrete.

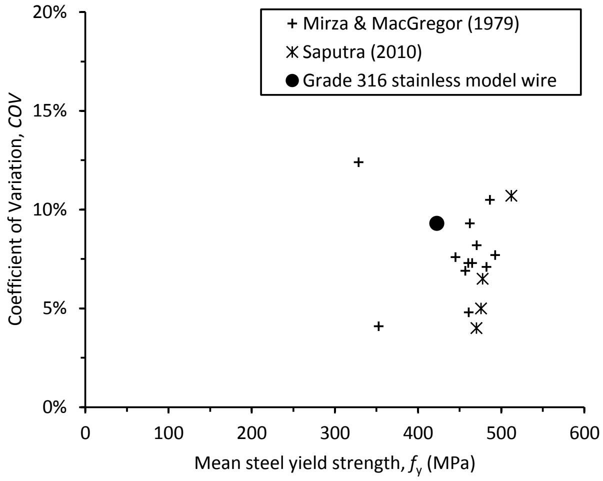

Figure 3 Variability of model reinforcement yield strength compared to typical values for conventional reinforcing bar.

strength consistent with concrete cast in-situ with good quality control (model concrete data taken from Table 1).

Figure 3 shows a comparison of the yield strength of the model reinforcement compared to typical values for steel reinforcing bar taken from the literature. The dataset of Mirza and MacGregor (1979) covers tests on bars of diameter between 10 – 43 mm, produced in the UK, Canada and USA. The smaller dataset of Saputra et al. (2010) includes bars of between 25 – 32 mm diameter, produced in Indonesia, Japan and USA. It should be noted that the prototype scale diameter of the model wire tested (30 mm) falls within both datasets and has a variability similar to that of conventional reinforcing bar. However, the test data indicate a mean yield strength which is lower ($\bar{f}_y = 422$ MPa) than the nominal value of 460 MPa shown in Figure 1 based on three preliminary tests.

3.2 *Reinforced structural elements*

Figure 4 shows the results of the bending tests for the model RC piles (Figure 4a) and piers (Figure 4b), to indicate the variability in the bending behaviour between nominally identical elements, both in terms of stiffness and strength. The data in this figure is shown at prototype scale (1:50). In each case, the prototype behaviour that the elements should reproduce is also shown. For the singly reinforced pile element, this was determined by hand calculation (see Knappett et al., 2011 for further details); for the pier, the uniform distribution of reinforcement complicated this and the prototype behaviour was instead determined using the numerical section analysis software USC_RC (Esmaeily and Xiao, 2002).

There is a very limited amount of data in the literature relating to the variability of reinforced concrete elements, principally because of the wide variability in possible designs, and the time required to cast a

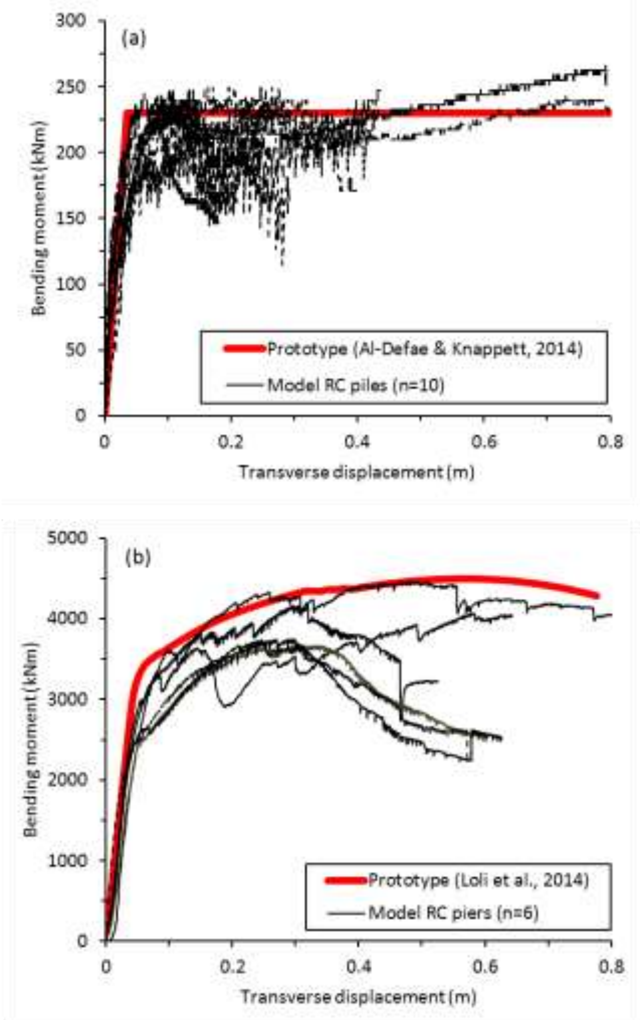

Figure 4 Four-point bending test results at prototype scale (1:50) for: (a) piles; and (b) piers (only t_{cure} = 28 day cases shown).

sufficient number of elements for testing in the laboratory. However, MacGregor et al. (1983) present a numerical analysis in which simulations have been performed on a range of different types of structural elements (including beams) to determine the variability in the capacity, by accounting for the variability of the various constituent parts within the governing equations. Values of the ultimate moment capacity (M_{ult}) were taken from the data shown in Figure 4 and the *COV* of this data is shown in Figure 5, compared to the slender beams simulated by MacGregor et al. (1983). The parameter A_s in the figure is the total cross-sectional area of the longitudinal reinforcement (so that A_s/bd is the '% steel area' or reinforcement ratio).

Figure 5 shows that the model RC elements when cured for 28 days appear to exhibit similar or lower variability than the conventional full-scale simulations. It is also demonstrated that if curing time was not controlled and the complete set of 10 pier tests was used to determine the *COV* for this case, the variability increases (as expected), but it is still reasonably representative of the conventional predictions.

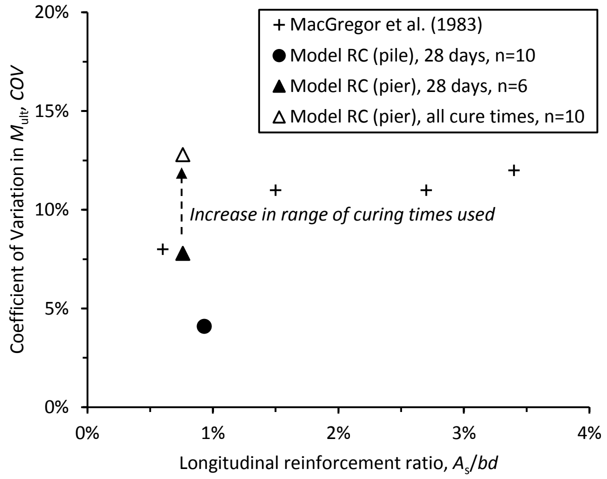

Figure 5 Variability of bending strength of model RC beams compared to simulated values for full-scale beams.

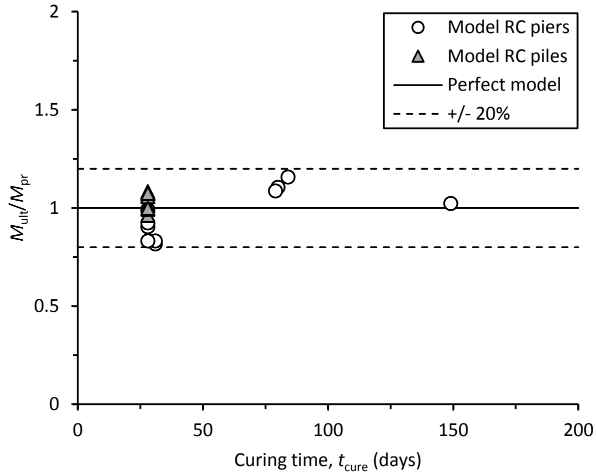

Figure 6 Effect of model volume and curing time on bending strength of model RC structural elements.

This suggests that if model RC elements were cast for a centrifuge test to be approximately 28 days old at the test time, but the test had to be postponed, it may not be necessary to recast new model RC elements. This is a useful finding, given the amount of preparation, casting and curing time required to make such small and detailed model elements.

3.3 *Effects of curing time and model volume*

Figure 6 shows the effects of curing time and model volume (through comparison of the piles and piers) on the moment capacity of the model RC elements. M_{ult} has been normalised by the target prototype moment capacity (M_{pr}) so that the two sections with very different values can be compared on the same plot. Considering first the piles (only tested at 28 days) a very close replication of the target moment capacity is achieved, as noted previously by Knappett et al. (2011). In comparison, the piers at $t_{cure} \approx 28$ days generally underpredict the target by up to 20% (though on average, around 12%). This is consistent with the pier section having a larger volume than the pile, which would suggest a slightly lower strength using the same materials based on fracture mechanics.

Previously (Knappett et al., 2011), it was suggested that the model RC could be used to produce prototypes of different sizes by varying the scaling factor. However, the results shown in Figure 6 suggest that models of different absolute size (here, by an order of magnitude in volume) can also be used without exhibiting significant over- or under-strength. This will provide greater flexibility in designing centrifuge models, particularly in cases where the scaling factor must by fixed by other considerations.

With increased curing, the underestimation in the piers reduces, and all of longer-term tests exhibit capacities which are slightly higher than the target. Along with Figure 5, this suggests that a longer wait between casting and testing will not only make the elements more variable in properties (the implication of which will be discussed in the following section), but also generally make them stronger. However, in both cases the effects are relatively small. Future testing of the pile section at different curing times would allow any size-dependency of the ageing effect to be determined.

4 IMPLICATIONS FOR MODEL DESIGN

It has already been demonstrated that the curing time and volume effects in the model RC are relatively small, providing flexibility in test scheduling and model design. However, the inherent variability of the model RC must also be taken into account when designing models which may induce structural failure. This will be demonstrated using the example of the rocking-isolated bridge pier experiments presented by Loli et al. (2014).

A soil-foundation-structure system such as a bridge pier will only be rocking isolated if the moment capacity of the foundation is lower than that of the structure. In Loli et al. (2014), two different foundations were considered to demonstrate the difference between rocking-isolated and conventional foundations. The former foundation was designed to have a deterministic moment capacity of 4.8 MNm, and the latter, 12.9 MNm. These values were confirmed by simulated push-overs in Loli et al. (2015). The moment capacity of the pier (as tested above) with the axial load of the bridge deck applied was 6.6 MNm. As this value is between the two footing moment capacities, this would appear to be suitable. However, this assumes that there is no possibility that due to material property variability in both the soil and the model RC pier, the rocking-isolated footing moment capacity is at one of its largest possible values and that this is higher than the moment capacity of the structure if this happens to be at one of its lowest possibilities (at which point it would cease to be rocking-isolated).

Figure 7 shows the probability density functions for the foundations and pier with the following assumptions: (i) the COV of the pier moment capacity is unchanged by axial load and only the mean capacity is increased; (ii) that the COV of the footing moment capacity is reflective of that of the friction angle used in its calculation. The value of COV selected is 10% after Schneider (1999); (iii) all moment capacities can be approximated by a normal distribution based on the deterministic calculations as the means.

The area beneath the overlapping parts of the footing and pier probability density function (pdf) curves (shaded zone in Figure 7) represents the probability of the rocking isolation failing. For the case shown (using *COV* = 7.8% based on t_{cure} = 28 days), the probability is 7%. If there was greater variability, say due to a greater variability in curing time within the experimental programme, the likelihood of the test not working as designed would increase. Using the larger *COV* for the piers from earlier (12.8%), the probability of failure increases to 17%.

This example demonstrates how the variability of model RC materials can be accounted for quantitatively in the design of centrifuge models including structural failure, to form a rational basis for decision making.

5 CONCLUSIONS

This paper has presented a study of the variability of a novel model RC material for use in centrifuge experiments which can simultaneously scale stiffness and strength. It has been shown that the variability of both the individual component properties and reinforced beams are similar to those of conventional field reinforced concrete. The effect of increased curing time increases variability and mean strengths, but the effect is small, suggesting that delays in a programme of centrifuge testing should not significantly affect the properties of the model RC elements. It has also been demonstrated how variability in the strengths associated with soil and structural failure modes can be quantitatively and statistically assessed in experimental design.

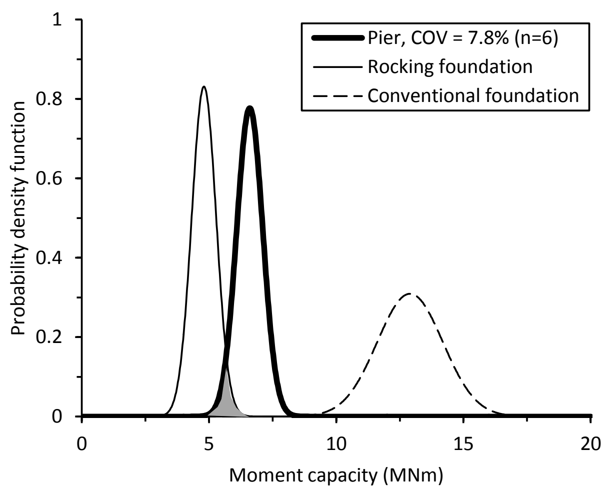

Figure 7 Determination of the probability of a rocking-isolated foundation not behaving as expected due to variability in the moment capacities.

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